

# Reply to Comment on “New limits on intrinsic charm in the nucleon from global analysis of parton distributions”

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We reply to the Comment of Brodsky and Gardner on our paper “New limits on intrinsic charm in the nucleon from global analysis of parton distributions” [Phys. Rev. Lett. **114**, 082002 (2015)]. We address a number of incorrect claims made about our fitting methodology, and elaborate how global QCD analysis of all available high-energy data provides no evidence for a large intrinsic charm component of the nucleon.

In a recent Comment [1], Brodsky and Gardner (BG) criticize our global PDF analysis [2] of all available high-energy scattering data, including those from fixed-target experiments at high  $x$  and low  $Q^2$ , which placed strong constraints on the magnitude of intrinsic charm (IC) in the nucleon. For a range of models of IC, the analysis [2] strongly disfavored large magnitudes of IC, with the momentum fraction carried by charm quarks  $\langle x \rangle_{\text{IC}}$  at most 0.5% at the  $4\sigma$  confidence level (CL).

BG claim that because our global analysis [2] uses  $\mathcal{O}(30)$  parameters, as is typical in all such fits, one must adopt a much larger tolerance criterion than  $\Delta\chi^2 = 1$ . In fact, it is well known that for Gaussian distributions parameter errors in  $\chi^2$  fits are determined by  $\Delta\chi^2 = 1$ , irrespective of the number of parameters in the fit [3, 4]. The parameter  $m$  in Table 38.2 of Ref. [3], for example, is the dimensionality of the error regions for joint distributions ( $m = 1$  for linear errors,  $m = 2$  for error ellipses, *etc.*), and has nothing to do with the total number of parameters in the fit. Actually, Fig. 38.2 of Ref. [3] involves the number of degrees of freedom of a fit (number of points – number of parameters) and not the number of parameters in the fit. For the determination of individual parameter errors, the correct dimension is  $m = 1$ , which gives  $\Delta\chi^2 = 1$  at the 68.3% CL. (For examples of error ellipses with  $m = 2$ , see Fig. 12 of Ref. [5].)

The parameter errors and  $\chi^2$  profiles related to one-dimensional probability distributions are correctly evaluated using  $\Delta\chi^2 = 1$ . Errors on other quantities are then computed using standard error propagation techniques, such as the Hessian method; they can also be used to produce error regions of different dimensionalities with the appropriate  $\Delta\chi^2$  criteria [3, 4]. Apparently, BG have confused the dimensionality of error regions with the number of independent parameters in a fit. Their claims about  $\Delta\chi^2$  are simply wrong.

Tolerance criteria  $\Delta\chi^2 > 1$  are used by some PDF groups [6–8] on purely phenomenological grounds, to account for tensions among different data sets, while others [5, 9, 10] use the standard  $\Delta\chi^2 = 1$ . The  $\chi^2$  profiles in [2] were presented as a function of  $\langle x \rangle_{\text{IC}}$ , so that  $\langle x \rangle_{\text{IC}}$

values for different tolerance choices can be easily compared. BG also suggest that our single parameter errors were obtained by fixing the other parameters at the  $\chi^2$  minimum. This is not true: we minimize the  $\chi^2$  with respect to all other parameters in the fit, as is standard procedure in global fits. Had we not properly refitted the complete model, the rise in the  $\chi^2$  away from the minimum would be even steeper than for the profiles shown in Fig. 1 of Ref. [2].

Inclusive DIS cross sections, such as those measured at SLAC, receive contributions from all quark flavors, so they cannot by themselves provide significant constraints on charm. The power of a global fit, however, lies in the correlation between different observables, with different weightings of quark flavors, within the framework of perturbative QCD. While the bulk of the data from SLAC [11] at large  $x$  lie below the charm threshold, cross sections below threshold constrain light quark distributions, which indirectly impacts on the determination of IC at the same kinematics. Our analysis also accounts for the suppression of charm production below and near the hadronic charm threshold [1, 2]. Implementing the suppression involves some model dependence in relating the partonic and hadronic charm thresholds [2, 6], and while this affects the quantitative limits (with partonic threshold factors alone  $\langle x \rangle_{\text{IC}}$  would be  $< 0.1\%$  at the  $5\sigma$  CL), the effects do not alter the overall conclusions about the magnitude of IC supported by the data.

To avoid dealing with complications from thresholds and other hadronic effects at low  $W^2$  and  $Q^2$ , many global PDF analyses impose more severe cuts on  $W^2$  and  $Q^2$  than those in Ref. [2]. While this simplifies the theoretical treatment, it also removes a significant amount of data at large  $x$  that could potentially impact the question of IC.

Recently, some PDF analyses [5, 7, 10] have relaxed the conventionally more restrictive  $W^2$  and  $Q^2$  cuts in order to better constrain large- $x$  PDFs. Such analyses benefit from increased statistics at large  $x$ , but require careful treatment of subleading  $1/Q^2$  and nuclear corrections. Our analysis [2] employs the standard treatment of

target mass corrections (TMCs) [12], phenomenological higher twists determined consistently within the same fit [5], and the latest technology in nuclear corrections [7]. Apparently confusing Refs. [5] and [7], BG assert that we model higher twists as isospin independent, and that our TMCs are problematic at  $x \rightarrow 1$ . In fact, our higher twist corrections do depend on isospin, as evident from Table III of Ref. [5], and are determined empirically without assuming any functional form.

Furthermore, the well-known threshold problem of TMCs at  $x = 1$  is relevant only at very low  $W^2$ , well below the cuts made in all global PDF analyses [12]. It is also not true that we neglect intrinsic strangeness and bottom: the  $s$  and  $\bar{s}$  PDFs are parametrized model independently at the input scale, and given our results for IC, intrinsic bottom is negligible for the current phenomenology [13].

Our global fit carefully propagates all statistical and systematic errors, both uncorrelated and correlated, including normalization, for all data sets used. (For details of the fitting code see Ref. [14].) For the SLAC data, our analysis uses the original hydrogen and deuterium cross sections [11] rather than the derived structure functions (obtained by combining measurements at different energies), which allows for a more exact treatment of point to point correlated errors. Aside from the SLAC data, other measurements, such as the NMC proton and deuteron cross sections [15] and the inclusive proton cross sections from HERA [16], also disfavor nonzero values of IC.

In addition to the fit of the standard high energy data sets used by most PDF groups, in Ref. [2] we also considered a fit including data from the EMC measurement of the charm structure function  $F_2^c$  [17] — sometimes cited [18] as providing evidence for large IC in the nucleon. In practice, the EMC data have strong tension with other measurements, and give a very large overall  $\chi^2/N_{\text{dat}}$  of  $\gtrsim 4$ , and a  $Q^2$  dependence incompatible with perturbative QCD. Several of the EMC data points at the highest  $x$  values ( $x \gtrsim 0.2$ ), where there are no other direct constraints from charm production experiments, lie systematically above all global fits, including ones with IC contributions [2]. At the same time, at low  $x$  values ( $x \lesssim 0.02$ ) where charm distributions are strongly constrained by HERA [19], however, the EMC data are significantly below the fitted results.

We thus disagree with the assertion of BG that  $\langle x \rangle_{\text{IC}} \sim \mathcal{O}(1\%)$  is “consistent with the analysis of the EMC measurements” [1]. No reasonable amount of nuclear corrections (which are, in fact, considered in Ref. [2]) or  $\Delta\chi^2$  tolerance can reconcile the EMC  $F_2^c$  data with the rest of the global data set within a QCD framework, without invoking a very peculiar shape for IC that is strongly at variance with all IC models [2, 20, 24]. Consequently, no

modern QCD analysis [5–10, 21–23] includes the EMC data in their fits. The MSTW analysis [6] compared  $F_2^c$  computed from their PDFs with the EMC charm measurements, and concluded that “If the EMC data are to be believed, there is no room for a very sizable intrinsic charm contribution.” We agree with this conclusion.

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